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Thermal infrared (IR) images of the ocean obtained from satellite sensors can be used to study ocean dynamics. Since satellite IR images often depict mesoscale features clearly (in the absence of cloud cover or excessive atmospheric water vapor), the use of AVHRR imagery for various oceanographic applications is expanding rapidly. The extraction of mesoscale ocean feature information from satellite images usually results from human interpretation of the sea surface temperature patterns visible in the image. With the proliferation of oceanographic analyses that utilize satellite data, it becomes highly desirable for certain applications to move from labor-intensive manual interpretation of satellite images, toward a capability for automated interpretation of these images.

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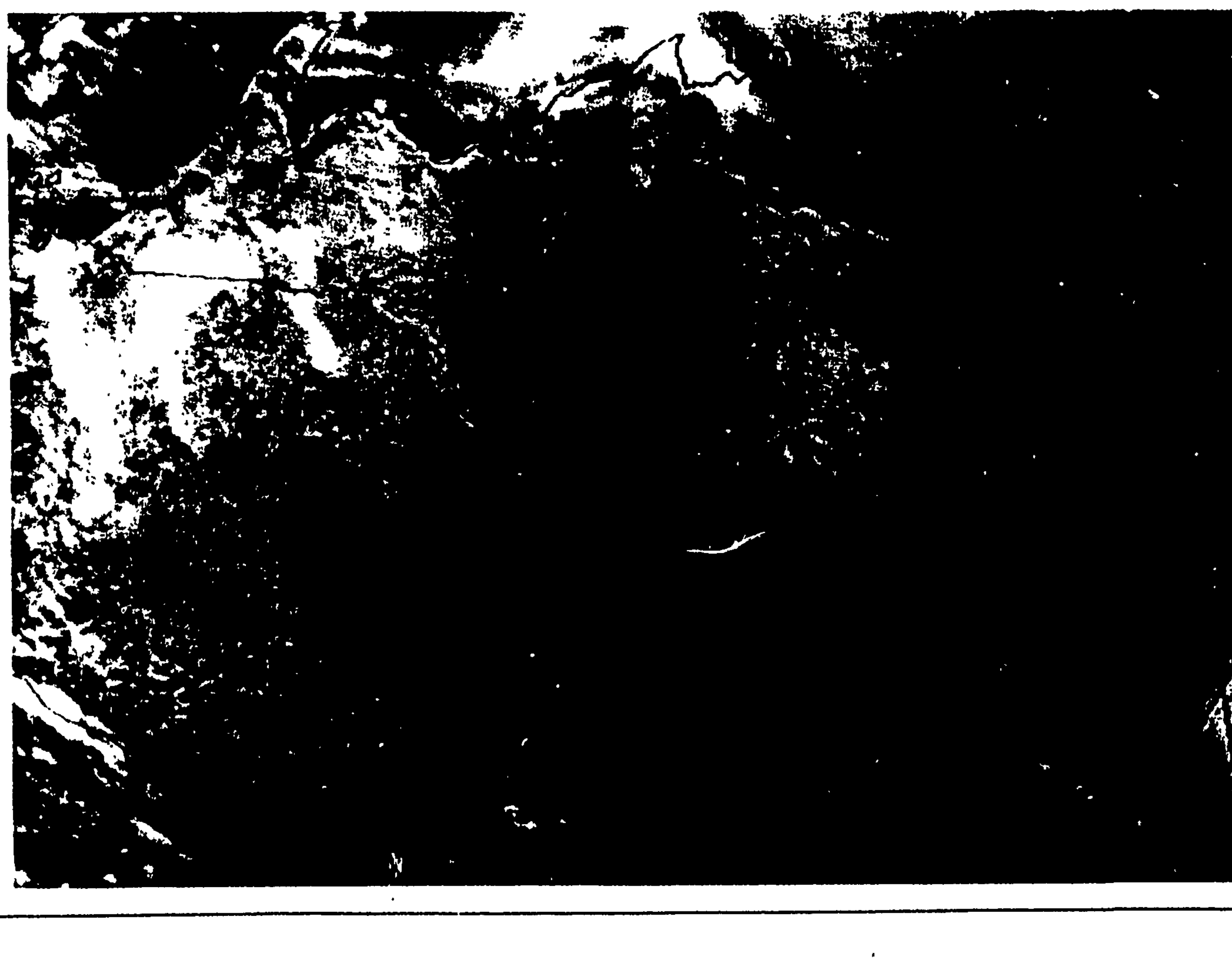

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EVALUATION OF THE NAVY'S SEMI-AUTOMATED MESOSCALE ANALYSIS SYSTEM (SAMAS)

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1. INTRODUCTION

Thermal infrared (IR) images of the ocean obtained from sateilite sensors can be used to study ocean dynamics. Since satellite IR images often depict mesoscale features clearly (in the absebce of cloud cover or excessive atmospheric water vapor), the use cf AVHRR imagery for various oceanographic applications is expanding rapidly. The extraction of mesoscale ocean ferture information from satellite images usually results from human interpretation of the sea surface temperature patterns visible in the image. With the proliferation of oceanographic analyses that utilize satellite data, it becomes highly desirable for certain applications to move from labor-intensive manual interpretation of satellite images, toward a capability for automated interpretation of these images.

Figure 1 shows a typical IR image of the Culf Stream region of the Northwest Atlantic. Images such as Figure 1 are the primary source of information leading to mesoscale analysis products like that shown in Figure 2. The analysis associated with the generation of Figure 2 was performed manually by analysts at the Naval Eastern Oceanography Center in Norfolk, Va. The long-range objective of our work is to develop image processing and artificial intelligence algorithms that would allow a computer to produce an analysis product such as Figure 2, given satellite imagery such as Figure 1. This is a difficult image analysis and understanding problem due to a lack of precise mathematical descriptions of the ocean features, coupled with the time-varying nature of these features and the complication of frequent partial obscuration by cloud cover. The total automation of this task is not presently feasible, but efforts toward that end will result in many tools that the analyst can use to reduce labor requirements and improve the quality and consistency of the analysis.

Several previous studies have addressed the automation of the analysis of IR satellite imagery for mesoscale features. Gerson and Gaborski (1977), Gerson *et al.* (1982), and Coulter (1983) have investigated the detection of the Gulf Stream. Janowitz (1985) and Nichol (1987) have reported some success in detection of eddies. The reader will find additional introductory material in these references.

This paper describes a prototype image analysis system that shows rudimentary skill in automatically locating both the Gulf Stream and eddies in IR images of the Gulf Stream region. The system has been applied to twelve test cases resulting in some preliminary performance statistics that are presented. Recommendations for future enhancements are also given.

2. APPROACH

The automated analysis of satellite imagery has been formulated conceptually to consist of three levels as shown in Figure 3. The lower level involves image segmentation using conventional image processing techniques. Segmentation, in general, can be edge-based or region-based. The output of the lower level is, therefore, either a set of edges or a set of regions, depending on the segmentation approach employed. At this lower level the analysis is focused on pixels. Oceanographic "knowlegde" does not enter into this level. The interest is simply in relationships between pixels in a local neighborhood that signify the presence of an intensity gradient (*i.e.*, an edge) or a region of uniform intensity.

The edges or regions detected in the low level segmenter are then passed to an intermediate level that performs the twofold function of labeling and feature synthesis. First, oceanographic identities, *i.e.*, North Wall, South Wall, warm eddy, cold eddy, etc. are assigned to each edge or region created by the segmenter. Edge or region fragments with identical labels are then collected (synthesized) into features and associated descriptive parameters such as position and radius are calculated. The labeling function can utilize ancillary data collected from other sensors, *e.g.*, an altimeter, as well as other factors such as continuity from the previous analysis, oceanographic context, bathymetry, climatology or anything else that might help. The labeling and feature synthesis functions are envisioned as a mixture of conventional image processing and artificial intelligence. Some algorithms may be pixel-based, others may be object oreinted.

A third analysis level, called the oceanographic expert system in Figure 3, contains a higher form of oceanographic knowledge. The data structure at this level is object oriented. Data sets consist of lists of object types, descriptive parameters, and coordinates. Artificial intelligence is the analysis tool applied in this upper level. For example, a rule base describing eddy motions

Fig. 1. Typical satellite IR image of the Gu ᶠ ᐟtream region of the North Atlantic. Darker shades represent warmer · .p.r. res and lighter shades represent cooler temperatures. A spatially variant enhancement has been applied to this image. Correspondence between absolute sea surface temperature and gray scale has been lost.

might be invoked at this level to move known eddies about in the analysis product during periods of cloud cover, when direct observation of the eddy is impossible

3. SEMI-AUTOMATED MESOSCALE ANALYSIS SYSTEM

The general approach outlined in the previous section has been translated into a specific implementation called the Semi-Automated Mesoscale Analysis System (SAMAS). Version 1.0 of SAMAS is shown in Figure 4. The components of Figure 4 are briefly described below.

3.1 Segmentation

An edge-based image segmentation scheme has been chosen for SAMAS Version 1.0. The edge detection algorthm, developed specifically for this application from image texture theory, has been described in Holyer and Peckinpaugh (1989). Cayula and Cornillion (1990) have also developed a special edge detection module for IR satellite imagery of the ocean Cambridge *et al.* (1990) are investigating the incorporation of both edge and region based ap,. oaches into an oceanographic image segmenter. Clearly, there are several options available for oceanographic image segmentation. Version 1 0 evaluated here utilized the original Holyer and Peckinpaugh (1989) edge detector. As a result of the other work underway in this area, future versions of SAMAS will undoubtedly benefit from improved segmentation

3 2 Feature Labeling

SAMAS feature labeling is performed by nonlinear probabilistic relaxation (Krishnakumar *et al.*, 1990). Relaxation labeling requires a first guess of the probabilities of edge segments belonging to each of the object types. This first guess is normally provided by taking the analysis product from the previous analysis period and moving the features forward in time to the present analysis date. Moving features ahead in time is accomplished by the oceanographic expert system shown at the right edge of Figure 4. Ititialization with the previous analysis weights temporal continuity heavily as a factor influencing feature

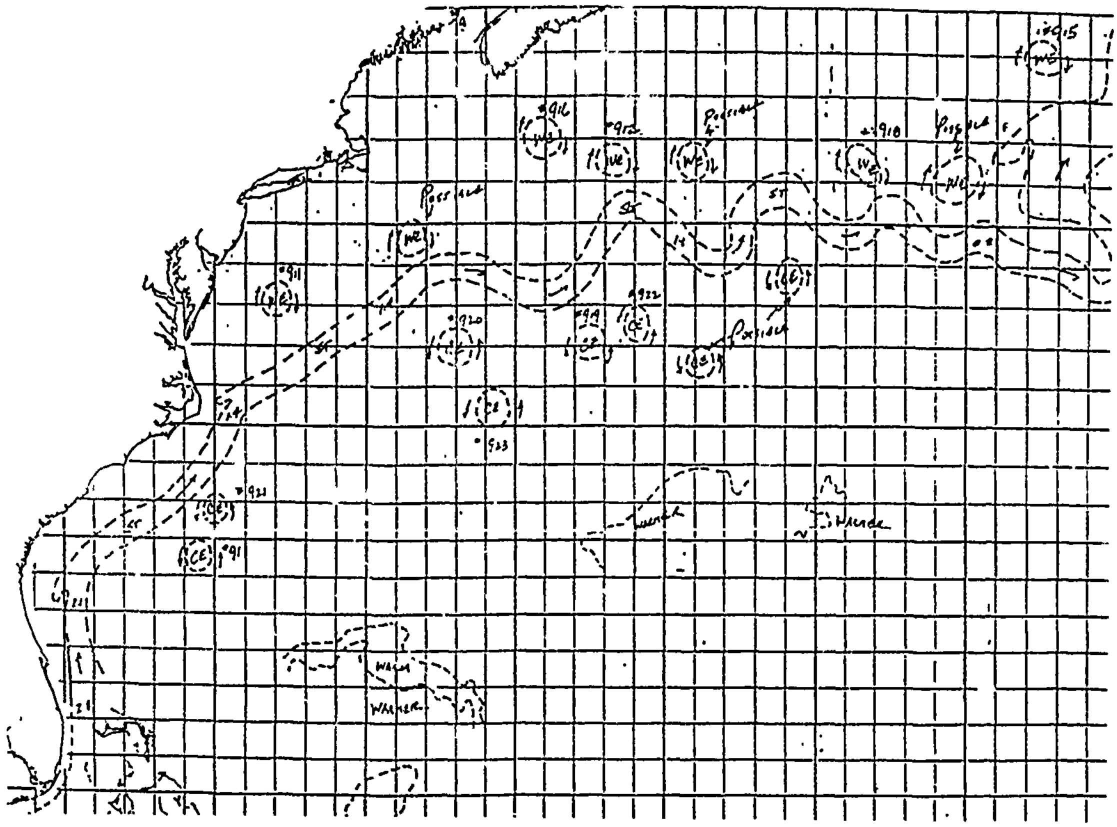

Fig. 2. Typical mesoscale analysis chart produced by the Naval Eastern Oceanographic Center in Norfolk Virginia.

labeling. This weighting is considered desirable since temporal continuity over scales of days is a major characteristic of mesoscale ocean features. Initial oceanographic label probabilities for each edge segment are then iteratively adjusted until they converge to values representing minimum uncertainty (or maximum consistency) in the assignment of one of the object labels to each edge pixel.

Relaxation labeling has been applied to a variety of image processing problems, such as pixel classification, that are related to this work (*e.g.*, Eklundh *et al.*, 1980 and Davis *et al.*, 1983). The relaxation labeling approach is elegantly described in Rosenfeld *et al.* (1976).

Genetic algorithms are under investigation as an alternate technique for labeling oceanographic features. Ankenbrandt *et al.* (1989) describe the genetic algorithm approach to feature labeling.

3.3 Feature Synthesis

Labeled edges provide fragmented representations of oceanographic features. For example, partial cloud cover may result in detection of only a few isolated pieces of the North Wall. Likewise, the complex spiral structures associated with eddies can lead to the association of numerous small edge fragments with an eddy. Constructing a continuous Gulf Stream or a complete circular eddy from fragmented renditions of these features is here called feature synthesis.

Molinelli and Flannigan (1987) have developed a method of constructing a continuous Gulf Stream from fragmented segments. Their method, which is incorporated into Version 1.0 of SAMAS, is based on a weighted sum of Gulf Stream normal modes. Normal modes are the eigenvectors of a covariance matrix describing Gulf Stream shapes. The normal mode weights required to produce a least-squares minimization of distance between the Gulf Stream edge segments and the resulting normal reconstruction are found by an iterative least-squares method. Gulf Stream shapes synthesized from fragments in this manner are continuous and carry through areas of could cover, giving an estimate of Gulf Stream location and shape beneath the clouds.

Warm and cold eddies are synthesized using the circular Hough transform (Duda and Hart, 1972). In general the Hough transform consists of remapping edge points from *image space* into a *parameter space*. The Hough transform for circles projects edge points into a 3-dimensional parameter space (the parameters being x-position, y-position, and radius). The parameter space is quantized into discrete bins and is known as the "accumulator array". Each edge point in the image that has been labeled as eddy "votes" for all those circles of which it may be a part by incrementing the appropriate accumulators. Local maxima in the accumulator array correspond to the circular shapes within the edge image. This method will find the most prominent eddies and give (x, y, r) parameter sets which permit filling in the eddies even when significant parts are missing.

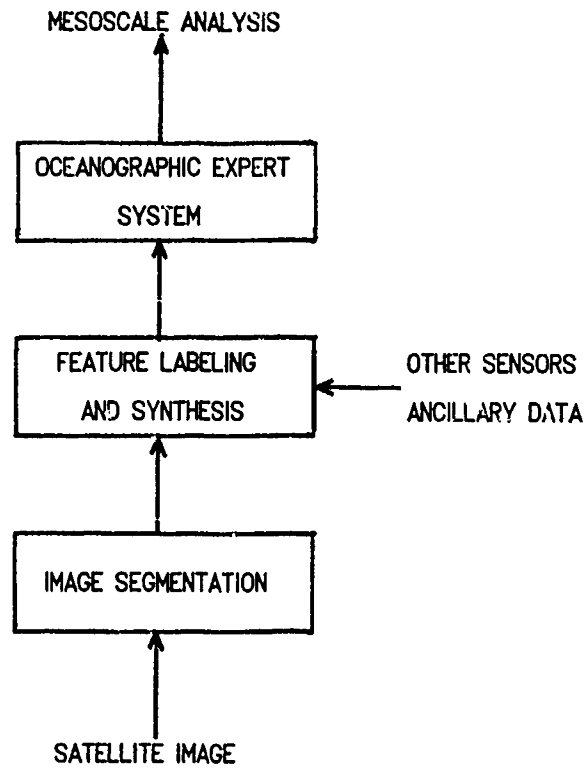

Fig. 3. A three-tiered approach to automated oceanographic satellite image analysis.

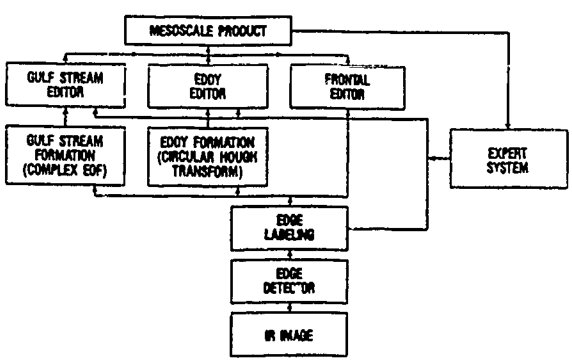

Fig. 4. A functional block diagram of SAMAS Version 1.0 automated image analysis system.

The circular Hough transform has been used in a variety of applications requiring the detection of circular features in images. For example, Cross (1988) applies it to find circular geologocal features in Landsat imagery; Kimme *et al.* (1975) apply it to the detection of tumors in chest radiographs.

3.4 Interactive Editors

SAMAS provides interactive software modules that allow the analyst to view the results and to delete or modify features that were automatically synthesized. Features that were missed by the automated techniques can be manually added by using the interactive editors.

Editor modules also provide record keeping functions by tagging each feature with position and size parameters, and with ancillary information such as the source of the feature, *e.g.*, automatically synthesized, propagated forward in time from the previous analysis via the expert system, or manually entered by the user.

3.5 Oceanographic Expert System

The oceanographic expert system consists of rules about time evolution of mesoscale features in the Gulf Stream region. Eddy motion, changes in eddy size with time, interaction between eddies and the Gulf Stream, and Gulf Stream phase velocities are factors covered by this rule-base (Lybanon *et al.*, 1986). Performance of this rule base in describing eddy motion has been evaluated by comparison with manually interpreted satellite imagery Eddy position forecasts out to 7 days have been shown to be better than the assumption of no motion in 63% of the 70 cases studied. Accuracy of the Gulf Stream dynamics in the expert system has not yet been evaluated.

The function of the expert system in SAMAS is twofold. First, it forecasts feature positions so that these dynamic features can be plotted in their approximate locations during periods of cloud cover, where direct observation is not possible. Second, the feature positions from the previous analysis are adjusted to provide a better first guess for relaxation labeling in the present analysis.

4. SAMAS PERFORMANCE EVALUATION

Twelve test cases from April and May of 1989 were selected for evaluation of the automated feature location performance of SAMAS. The data set contained 36 images. One test case consisted of anywhere from 2 to 5 of these images mosaiced together by maximum temperature techniques, to give a single test image. Maximum temperature compositing was performed to minimize cloud cover in the test images. Figure 5 shows the test case image that is the most cloud free of the twelve. All cases will be shown in the poster session.

The twelve test cases were processed using the algorithms described in Section 3. The result was an automatically generated mesoscale analysis for each case. The automated analysis of the test image shown in Figure 5 is given in Figure 6. Note that Figure 6 was produced totally without human interpretive input, *i.e.*, the interavtive editors available in SAMAS were not used in this case. Positions of the features seen in Figure 6 and in the other eleven automatically generated analysis products were compared with feature positions determined from manual interpretation of these images in conjunction with the GEOSAT Ocean Applications Program (GOAP) (Lybanon *et al.*, 1990).

Preliminary comparisons show, for example, that the prominent warm eddy to the north of the Gulf Stream in Figure 5 was detected automatically in 90% of the cases where the human analyst was able to locate it. The mean distance between centers of this eddy, as

Fig. 5 A test image used to evaluate SAMAS Version 1.0. Enhancement is the same as in Figure 1.

determined manually and automatically, was 27 km. The automatic algorithms assigned a radius value to this eddy that was, on the average, 30% larger than the radius assigned by the human interpreter. Additional accuracy results for cold eddies and for Gulf Stream position will be presented on the poster.

5 CONCLUSIONS

The feasibility of automated analysis of satellite imagery for positions of mesoscale ocean features has been demonstrared. Weaknesses in Version 1 0 have been identified and now form the rational for further research. Specifically, improvements have been initiated in the area of segmentation, where a new segmenter utilizing both edge and region information, is under development (Cambridge *et al.*, 1990). This first evaluation has also revealed that the feature labeling algorithm is too closely tied to the initial guess. Improvements in this area are also underway (Krishnakumar *et al.*, 1990). A new approach to feature labeling using genetic algorithms is also under investigation (Ankenbrandt *et al.*, 1989).

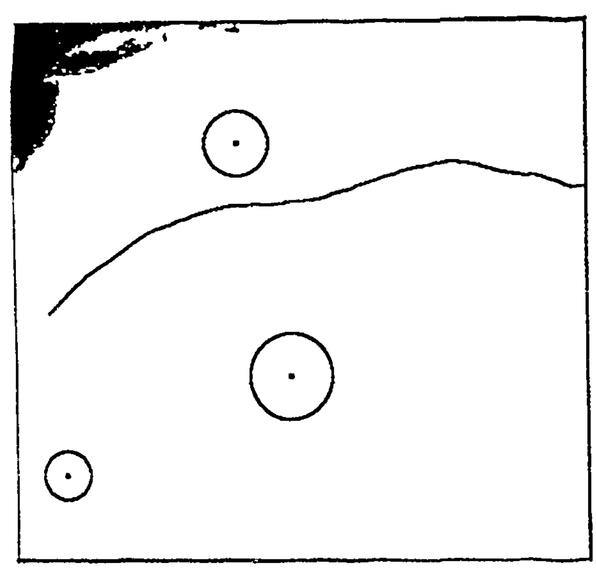

Fig. 6. Automated analysis of Figure 5 showing the Gulf Stream position, one warm eddy, and two cold eddies.

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